ENSO, CLIMATE VARIABILITY, AND THE RAPANUI: PART I. THE BASICS

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INTRODUCTION

In Part I we examine the definitions and history of ENSO, ask why we care about it, and make a stab at the curious equatorial dynamics behind it. The goal is a tutorial which will help non-oceanographers discern relevant papers amidst the voluminous ENSO literature.

In Part II (the next issue of RNJ) we will see that whatever one thinks of equatorial dynamics theory, the actual ENSO data are baffling without an idealized model to organize it. After sorting out what is going on, we look at the particular effects of ENSO on Rapa Nui.

There is a wealth of information relating to ENSO on the web (including a great deal of obsolete and unreliable material!). Most web sites are volatile and even those run by established institutions are dynamic and subject to updates and revisions. I can no longer regenerate some of the illustrations I have taken from web pages. Nonetheless, the URLs which I cite will contain material which is reliable, interesting, colorful, sometimes animated, and often more timely than any publication.

El Niño, the EN of ENSO, is a periodic appearance of warm water off the coast of Peru, which is blamed for many unpleasant events there and elsewhere. The Southern Oscillation, the SO of ENSO, is a quasi-regular variation in the trans-Pacific mean atmospheric pressure. It is the parent of El Niño, the determinant of the hydroclimate of Western Polynesia (Rougerie and Rancher 1994), and the largest source of global interannual climatic variability (Diaz and Markgraf 1992:1; see also Diaz and Markgraf 2000). Rapa Nui, at 27°S, 251°E, is at the center of the Easter Island High-pressure zone, a pole of the Southern Oscillation.

Climate variability may have been the bullet behind the 16^{th}-17^{th} century collapse of Rapanui culture (McCall 1993), as it seems to have been for the Maya a millennium earlier (Hodell et al. 1995, Fagan 1999). Or perhaps climate was only the trigger. Any vagaries of climate at Rapa Nui might be exacerbated by ENSO (Ruzmaikin 1999), perhaps pushing a tolerable condition over the limit.

With no consensus on this question, or on whether the Rapanui needed help to destroy their culture (Flenley 1996), it is useful to survey what is known of ENSO, the more so since there are few papers which mention both 'ENSO' and 'Easter Island'. The fate of the Rapanui, whether caused by ecodestruction or climate change, holds lessons for our own inadvertent experiments in these fields (Asimov & Pohl 1991).

THE SOUTHERN OSCILLATION

Figure 1 shows the correlation of pressure anomalies that comprise the Southern Oscillation. The Southern Oscillation Index (SOI) is defined as the difference in sea-level atmospheric pressure (SLP) at Darwin, Australia (12°S, 131°E), and Tahiti (17°S, 210°E). Such permanent pressure distributions are functions of geography (the placement of the continents and the distribution of reflectivity) and planetary astronomy (the tilt of the Earth's axis and its relation to perihelion). Galapagos or Rapa Nui might have made a better eastern station (Harrison and Larkin 1996), but neither has long-term weather records. Because barometers are self-calibrating, old pressure measurements are more reliable than old temperature measurements, particularly of 'surface' seawater when no record was kept of how the measurement was made. Good instrumental data for the SOI reach further into the past than most climate records.

The Southern Oscillation was noticed in 1877 by civil servants of the British Empire, through simultaneous droughts in Australia and India, where 6 million people died (12 million Chinese died also, unnoticed by the West; Davis 2000). Russell

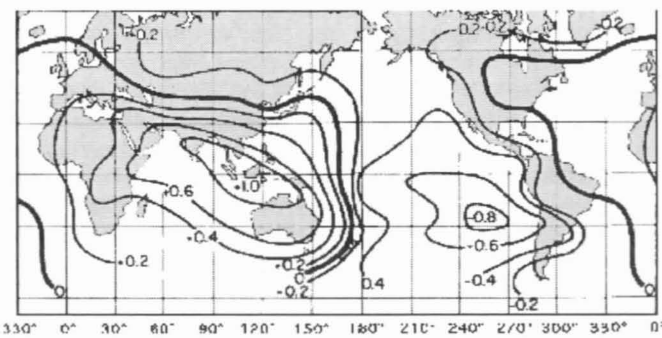

Figure 1. The Southern Oscillation (Walker 1924). The contours are the correlation of annual sea-level air-pressure anomalies with simultaneous anomalies in Djakarta, Indonesia (after Berlage 1957).

(1896) saw the high correlation between such droughts, and meteorologists took note (Hildebrandsson 1897, Lockyer 1906). The correlation between Indian droughts and El Niño is shown at http://rainbow.ldeo.columbia.edu/dl/seminars/nino3corr/ in a subtle color graph. Brooks and Braby (1921) noticed that Polynesian wet and dry periods were correlated with the surface wind field. Walker (1924) synthesized global variability in terms of the SO of Figure 1, but it was not until Leighly's (1933) neglected paper that the link between the SO and Polynesian weather was recognized.

Figure 2 shows the SOI from 1876 to 2000, for the sake of those looking for SO signals on Rapa Nui. It will be seen in Figure 3 that the SOI is similar to, but not identical to, the El Niño Index, ENI. A tabular reconstruction based on dendrochronology back to 1706 can be found in Stahle et al. (1998).

EL NIÑO

Of the many definitions of El Niño, the Japan Meteorological Agency's is a robust measurement that accurately identifies past ENSO events (Trenberth 1997). It is a five month running mean of spatially averaged sea-surface temperature

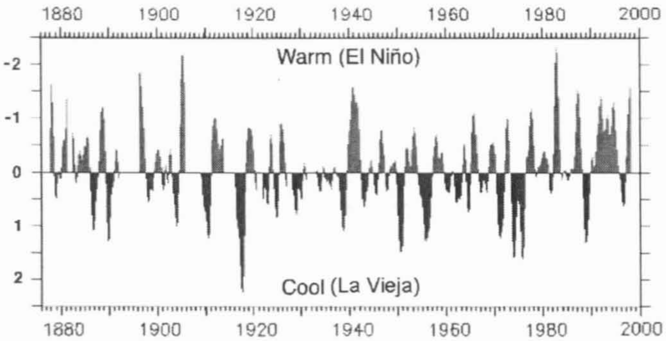

Figure 2. The historical Southern Oscillation Index (inverted for comparison with Figure 3, after http://www. pmel.noaa.gov/~kessler/ ENSO/soi-1876-1998.gif

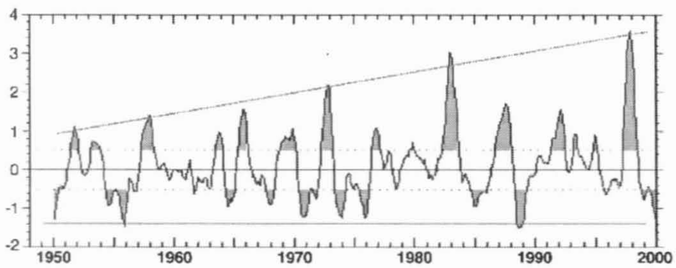

Figure 3. Monthly JMA El Niño Index for the period 1975-2000. The (eyeball) trend lines running through the extrema might suggest that as the planet warms, La Niñas remain at the same temperature (deep water warms slowly) while surface-water El Niños become increasingly warm, but a longer time series shows that such excursions are a normal aspect of interannual variability (Harrison and Larkin 1997).

(SST) anomalies over the equatorial Pacific: 4°S to 4°N, 210°E to 270°E. If index values are • 0.5°C for six consecutive months including October to December, the ENSO year of October through the following September is categorized as El Niño. (e. g., the El Niño year 1970 starts October 1970 and ends September 1971.) If index values are • 0.5°, it is a La Niña year (Figure 2). Years that fulfill neither of these conditions are neutral.

One often sees reference to 'NINO n', where 'n' indicates an ENSO monitoring region. These are:

NINO 1+2 0° to 10°S; 270°E to 280°E (i.e. Peruvian coastal waters)
NINO 3 5°N to 5°S; 210°E to 270°E
NINO 3.4 5°N to 5°S; 190°E to 240°E
NINO 3.5 5°N to 10°S, 180°E to 240°E, 0.3°C Trenberth and Hoar (1996)
NINO 4 5°N to 5°S; 160°E to 210°E

This variety represents attempts to find the most useful prognostic area, sometimes with different criteria in mind.

From 1949 to present, the JMA Index is based on observed data; for the years 1868 to 1948 it is a computer reconstruction (Meyers et al. 1997). ENI values for each month 1868 to 1949 are available at ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/. For an annual dendrochronological reconstruction 1408 to 1978 see Cook (2000).

The cold tongue of upwelled water along the eastern Pacific Equator—the home of El Niños—is the major site of heat absorption by the ocean (Hsiung 1985). It is thus no surprise that changes in this region have global consequences.

There are good reasons why El Niño remains more mysterious than other ocean circulation patterns, such as the Gulf Stream. These include:

Economics: The Gulf Stream affected Atlantic shipping early on. Its climatic effects on Northern Europe were also recognized early. El Niño's direct effects were until recently only of local importance; its teleconnections—however disastrous—only statistically visible.

Accessibility: The Gulf Stream runs past the Rosenstiel School of Marine and Atmospheric Science (Univ. Miami), the Graduate College of Marine Studies (Univ. Delaware), Lamont-Doherty Earth Observatory (Columbia Univ.), the Graduate School of Oceanography (Univ. of Rhode Island), Woods Hole Oceanographic Institute, and similar centers. The eastern tropical Pacific is far away.

Complexity: The Gulf Stream is a relatively simple, narrow, consistent, localized current. Pacific equatorial currents form a complicated, broad, highly variable, and extended system.

Ease of modeling: The Gulf Stream can be modeled in a rotating tank. Observing simple dye-distribution experiments leads to insights into its dynamics. There is no comparable tool available for equatorial systems, which must be modeled mathematically by a sequence of increasingly complex models.

Boundary conditions: The input to the Gulf Stream is Atlantic surface water, which presents no puzzles to speak of. Most of it re-circulates; its contribution to the important question of North Atlantic Deep Water formation is indirect. The western end of the ENSO system is the Indonesian Archipelago, whose shorelines are steeply angled, whose shallow and convoluted passages form the only significant connection between ocean basins, and whose highly variable current systems are only now being studied in detail (Nof 1996, Sprintall et al. 2000a). Figure 4 shows the complex nature of the flow path through the Archipelago. Shutting this flow path in models causes major changes in the ENSO system.

WHY DO WE CARE? TELECONNECTIONS

Although El Niños are strictly equatorial phenomena, they may be relevant to Rapa Nui because of climatological 'teleconnections' which affect temperature, rainfall, storms, fish catch, wild fires, etc. in areas far outside the Eastern Equatorial Pacific. The historical effects of El Niños on Rapa Nui, and on Polynesian settlement in general, remain to be clarified, but the range of possibilities is known from other locations.

Indonesian drought in 1998 led to extensive rainforest wildfires (not all of which were started by natural causes). El Niño is associated with severe winter weather in the US (van Loon and Madden 1981, van Loon and Rogers 1981), tempera-

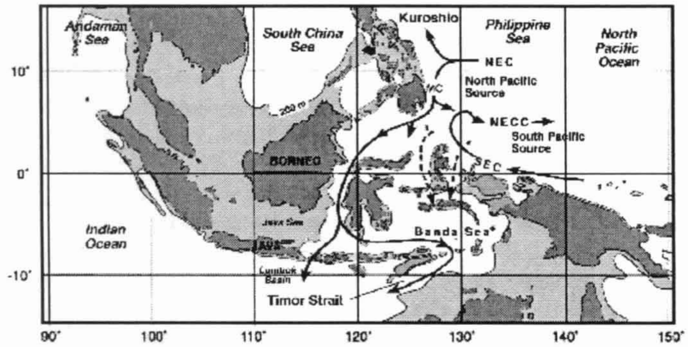

Figure 4 The complex structure of the Indonesian archipelago, which forms the western boundary of the ENSO system. The arrows show the mean flow; actual flow is apparently oscillatory and may be an important aspect of El Niño formation (after Nof, 1996).

ture fluctuations in the Northern hemisphere (Pan and Oort 1983), February to May rainfall over northeast Brazil, and off-equatorial SST anomalies in the tropical Atlantic (Wallace et al. 1998).

The Aleutian Low strengthens, splitting the subtropical jet stream (McPhaden et al. 1998) and altering storm tracks and precipitation (Green et al. 1997) over the US. The Kuroshio may be deflected by decade-old Rossby waves generated by El Niño (Jacobs et al. 1994). A zonal wave circulating in the Antarctic Circumpolar Current generates coherent oscillations in sea-surface temperature (SST), sea-level pressure (SLP), sea ice, and meridional winds, and may derive from ENSO (White and Peterson 1996). ENSO teleconnections influence Atlantic-basin variability (Enfield and Mayer 1997), and the ENSO/monsoon connection has been debated since the dawn of global meteorology (Tourre and White 1995).

Many teleconnections have <10% correlation with ENSO, becoming evident only after statistical analysis. They are nevertheless important because they affect large areas, with very real social and economic consequences.

Bove (1999) finds that El Niños reduce tornados in the southern-plain states of the US, and inhibit multiple tornado outbreaks, while La Niñas increase them in the Ohio River Valley and Deep South and facilitate multiple tornados. Bove et al. (1998) find that the probability of 2 or more Atlantic hurricanes making landfall in the U.S. is 66% during La Niñas, 48% during neutral years, and 28% during El Niños because the relocated jet stream sweeps the tops off of developing hurricanes. Pacific hurricanes ('typhoons' and 'cyclones') increase in frequency during El Niños because they have more warm water (>28°C) over which to form.

To repeat an earlier comment (MacIntyre 1999), the US National Academy of Science's decade-to-century climate-fluctuation group collected anecdotal effects of the 1997 El Niño (Lowell Smith, personal communication). Events of the sort which might have affected Rapa Nui include: 10 Galapagos sea lions where 100s were expected, rain in the Galapagos causing vegetation to overgrow seabird nesting sites, Peruvian fish meal production down 80%, drought in Hawai'i affecting forest-product production, poor sugar harvest in Cuba, forest fires in Mexico and South East Asia, undernourished bait fish in California waters, absence of pinnipeds and cetaceans from Eastern Pacific water over 200 m depth, famine and widespread child malnutrition in Mindanao. Any such event occurring on Rapa Nui might have had serious social repercussions.

Webster and Palmer (1997) add catastrophic flooding in Central Europe and along the Pacific Coast of South America, an increase in water-borne diseases (hepatitis, dysentery, typhoid, and cholera) and vector-carried diseases (malaria, dengue and yellow fevers, encephalitis, plague, hantavirus, and schistosomiasis). Epstein (1995) discusses basic public-health and natural-disaster problems associated with ENSO.

According to some estimates, there were 22,000 deaths worldwide and $36B in US losses to the 1997 El Niño, yet the net effect in the US may have been a $16B benefit and 650 fewer deaths from winter exposure. Losses in one fishery are often balanced by gains in another, making El Niño prediction an important component of the oxymoronic ideal of rational fishery management (Glantz 2000).

Why and Where are Fish Affected?

Many tropical corals, sponges, and molluscs depend upon intercellular photosynthetic algal symbionts for much of their food. At high light levels and high temperatures (>28°), the symbionts apparently produce enough oxygen to become toxic to their hosts (Sandeman 1989), who expel them, leaving themselves bleached, undernourished, unable to reproduce, and vulnerable to disease and predation (Pecheux 1995). The symbionts do not necessarily return when the water cools. Some feel that tropical corals will be exterminated by 2100 (Hoech-Guldberg 1999).

Dead marine organisms and fecal pellets sink, so oceanic nutrients end up in deep water. Wind-driven upwelling returns them to the surface, maintaining the phytoplankton–copepod–baitfish–fish–human food chain. Anything that affects upwelling affects people. The poleward coastal waves of an El Niño (see below) depress the thermocline and warm the surface by reducing cool upwelling, raising sea level by 15 to 30 cm, changing near-shore wind and storm patterns, and causing ecological upsets in California waters too complex to discuss here. (see http://cwatchwc.ucsd.edu/cgi-bin/elnino.cgi for further information).

The Peruvian anchoveta fishery is particularly dependent upon upwelling off Peru, and between persistent overfishing (20% of the global catch) and the 1972 El Niño, suffered a 10-year collapse. Anchoveta being a major source of fish meal used as agricultural fertilizer, this lead to knock-on effects far from the equator (McPhaden 2000).

The 1997 El Niño, in some ways the strongest ever observed, resulted in depleted macronutrients throughout the central Pacific to a depth of 100 m, with chlorophyll concentration and primary production comparable to oligotrophic central gyres (Strutton and Chavez 2000).

Equatorial primary productivity doubled from South America as far west as 220°E during the 1991 El Niño – 1992 La Niña transition. Contrary to received wisdom, which held that the cold waters are productive because they return macronutrients (nitrate, silicate, and phosphate) to the surface, the increased productivity is micronutrient controlled, apparently by iron. This suggests that the warm El Niño water depresses the mineral-rich Equatorial Undercurrent (EUC) and prevents its upwelling (Barber et al. 1996). A major component of the Equatorial Undercurrent originates in the West Pacific archipelago, picking up its characteristic trace-metal signature from the rivers of volcanic islands (Butt and Lindstrom 1994).

ENSO IS NOT THE ONLY VILLAIN

Before proceeding, we must absolve El Niño of guilt for all bad weather.

The weather system which most affects North America is the Pacific-North American (PNA) system. Some workers (Lau 1997; Saravanan 1998) describe the PNA as a natural mode of the atmosphere which is strongly modulated by ENSO. A slight exaggeration of this view—which has been picked up by the communications media—has the effect of laying all climatic disasters at the feet of El Niño. In contrast, the GCM model calculations and statistical analysis of Strauss and Shukla (1999) find that ENSO and PNA are distinct patterns, and that each is capable of causing trouble on its own.

A readable summary of this question is Voituriez and Jacques (2000).

PLANETARY FLUID DYNAMICS

Before we can make sense of ENSO, we need to be familiar with some counter-intuitive results of the Earth's rotation on geophysical fluid dynamics.

Equilibrium motions

The equilibrium state is not at rest, but a 'geostrophic' balance between pressure gradients and the Coriolis force $f = 2\bullet \sin(\varphi)$, where Ω is the Earth's angular velocity and φ the latitude; f is thus 0 at the equator. (f is a non-rotating, 2-dimensional replacement for the conservation of angular momentum on a rotating, 3-D world, introduced because it greatly simplifies the arithmetic.)

Away from the equator (and topographic impediments),

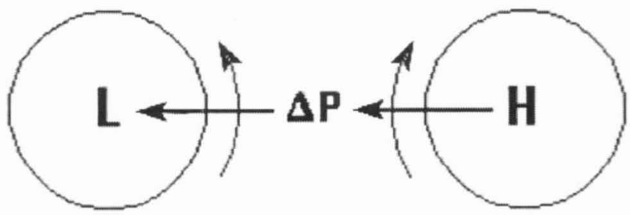

Figure 5. Equilibrium motion around low- and high-pressure regions is along isobars, a pattern familiar from weather maps. Deflection is to the right in the northern hemisphere (shown) and left in the southern.

equilibrium motion is along isobars and often circular, as in Figure 5. A consequence of geostrophy is a unidirectional wave guide at the equator, about 4° wide (Figure 6). Eastward motions converge and are trapped by the equator; westward motions are divergent and escape. Continuous eastward motion is possible at the equator itself.

The convergent horizontal flow at the equator creates a front between two water masses, which may have very different temperature and salinity characteristics. In addition, the convergence must be balanced in some way, usually by downwelling, so that $dv/dy = -dw/dz$. Downwelling while the Warm Pool is growing can depress the thermocline by 50 m in 20 days, or 2.5m/day (Kessler, personal communication).

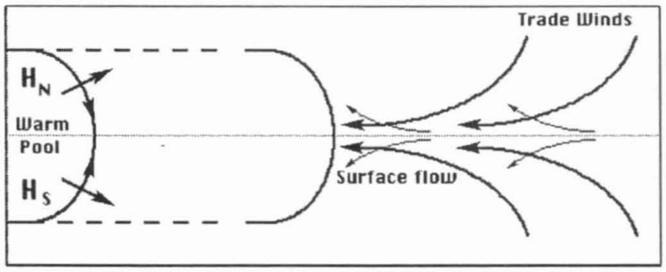

Figure 6. The equatorial wave guide. These are the wind and water movements that contain the western Pacific Warm Pool while allowing it to grow eastward.

Another nonintuitive consequence is that surface water moves to the right of the wind stress (in the northern hemisphere) whenever it can, as indicated in Figure 6. Surface water driven westward by the trades moves away from the equator and is replaced by upwelled cooler water from below. Contrary to appearances, the westward drift does not directly contribute heat to the Warm Pool because of this upwelling. A simple parameterization of this process is that SST is proportional to the ratio of wind stress τ to an isotherm depth Z(23°), $SST = T_0 - A\tau/Z(23°)$ (Kessler and McPhaden 1995b). Warm water input to the Warm Pool arrives by a more circuitous route.

Energy is hard to extract

Moving systems retain their potential energy. The ocean is so frictionless (except along shores and the bottom) that organized systems such as eddies formed in the tropics north of Madagascar can be followed as they are entrained in the Agulhas Current, swept around the Cape of Good Hope and up the Benguela Current toward the equator, cross the Atlantic, and again head east. Such eddies are the dynamical analog of atmospheric hurricanes (Gill 1982:195), surviving longer because they are not in frictional contact with a boundary.

The Trade Winds are the surface component of the Hadley Cells, in which warm air rises at the equator (giving us the doldrums which becalmed the Ancient Mariner), dumps much of its moisture as it rises and cools, flows poleward (and to the east) until it reaches 30°, where it sinks. This dry descending air creates the horse latitudes at sea and deserts on land: the American Southwest, the Sahara and Arabian Deserts, the Australian, the Atacama, and the Kalahari. That component of the atmospheric circulation which flows directly eastward above the equator is called the Walker Cell; its rising pole, based over the western Pacific equator, is the Walker Center, the major source of stratospheric water vapor.

Isopycnal motions

Density variations are small in the ocean. Nevertheless, the frictionless nature of oceanic motions means that water parcels can insinuate themselves along isopycnals (surfaces of constant density) with little mixing. Motion along isopycnals is the ordinary pathway for moving water masses in the ocean.

Wind stress and curl

The force exerted by the winds on the ocean—the wind stress—is at right angles to the wind and proportional to the square of the wind speed.

The trade winds are easterlies, and poleward of the trades are the westerlies. A giant horizontal windmill would rotate clockwise in the northern hemisphere and counterclockwise in the southern. This rotation is the 'wind curl' (which has a more precise definition in terms of differential velocities).

The resulting motion of surface water is a pair of extra-tropical convergences, and thus the forcing of water downwards. These water masses drift equatorward as they subside and eventually become involved in the complex equatorial current system. (A convenient generalization of motion on a rotating sphere is that moving fluids can conserve angular momentum by remaining on the surface of a cylinder coaxial with the sphere. Hence the tendency to sink as they move equator ward.) The net effect is that events in the central oceans may have repercussions on equatorial events (such as El Niños) several years later.

Equatorial currents

Figure 7 shows some of the variety of equatorial currents that can be obtained with a relatively simple model. We will see later that the actual system is considerably more complex, because of wind reversals, because the effective atmospheric equator (the Intertropical Convergence Zone, or ITCZ) is usually displaced 3° to 8° north of the geographical equator by the imbalance of land and water areas in the north and south Pacific, and because a small southerly component to the wind—present whenever the ITCZ is north of the equator—complicates the simple model beyond recognition.

In addition, there is an unexplained array of deeper zonal flows on and about the equator (e.g., Firing et al. 1998) which probably do not concern us.

Kelvin and Rossby Waves

Ocean-surface waves occur at the interface of two fluids where the density difference $\Delta\rho$ • 1025 (kg/m^3) and $(\Delta\rho/\rho)$ • 1. It takes far less energy to excite interfacial waves, where the density ratio ρ_1/ρ_2 • 1, as it is across the thermocline. Such interfacial 'baroclinic' waves accordingly have large amplitude (10s of meters) at density discontinuities, while leaving the surface almost flat. *Baroclinic* implies pressure gradients—and hence motion—along isopycnals. In the long-wave (shallow-water) approximation, the speed of a wave is $c = [g(\Delta\rho/\rho)H]^{1/2}$ where g is gravitational acceleration (ca. 10 m/s^2), and H is the depth—in our case, the depth to the thermocline, so that here c is on the order of $(10{*}0.004{*}100)^{1/2}$ • 2 m/s.

'Dearly beloved by equatorial oceanographers are the eigensolutions of an unforced stratified fluid linearized about a resting basic state, horizontally homogeneous except for a linear [latitude] dependence of the Coriolis parameter', say Neelin et al. (1998). These solutions are the first and second (Kessler and McPhaden 1995a) baroclinic Kelvin (equatorial, eastward moving, rapid) and Rossby (off-equator, westward moving, slow) waves, involving linear combinations of parabolic cylinder functions (Gill 1982). Since few others have ever seen a parabolic cylinder function (the curious may find them in Abramowitz and Stegun 1965), and since such waves are customarily discussed after several hundred pages of differential equations in physical oceanography texts, this description is not particularly helpful. We will try for a less formal image.

One non-intuitive feature is that the water waves met in freshman physics classes are surface gravity waves, which transport energy, but not appreciable amounts of matter. It is the wave shape which propagates, leaving the fluid in place. This is not the case for Kelvin waves, in which the whole body of water above the thermocline is in approximately uniform motion.

Kelvin waves may be 1000s of km long and imperceptible to the eye. They show up as changes in mean sea level and displacement of the thermocline. An equatorial Kelvin wave may have any zonal profile forced by the wind; its meridional profile is a Gaussian varying as $\exp[-(y/\sigma)^2]$, where σ is the

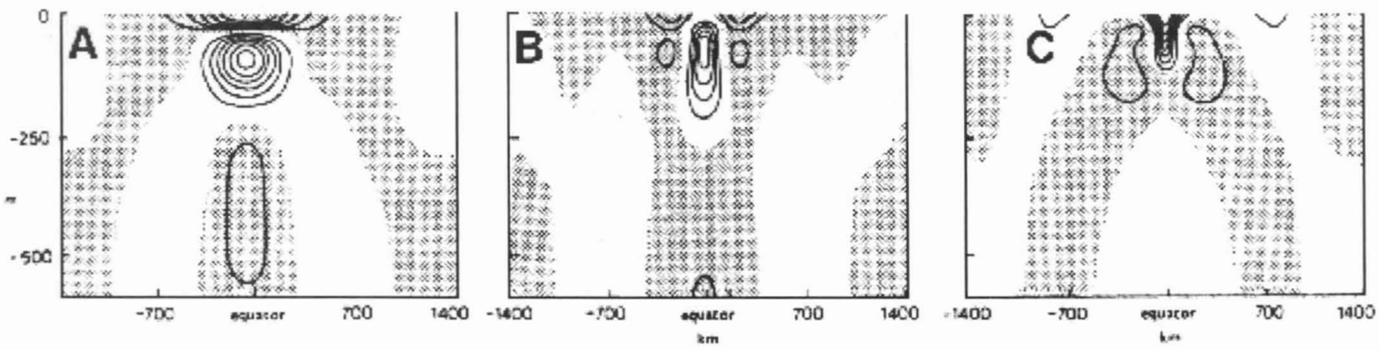

Figure 7. Currents developed by a continuously stratified equatorial model with a wind stress of 0.5 dyne/cm^2. Contour interval is 10 cm/s, the zero contour is omitted, and shaded regions indicate westward flow. A: Easterly wind with nonlinearities removed. B: Easterly wind with nonlinearities. C: Westerly wind with nonlinearities. The system becomes considerably more complex if the winds have a southerly component (After Philander and Pacanowski 1980).

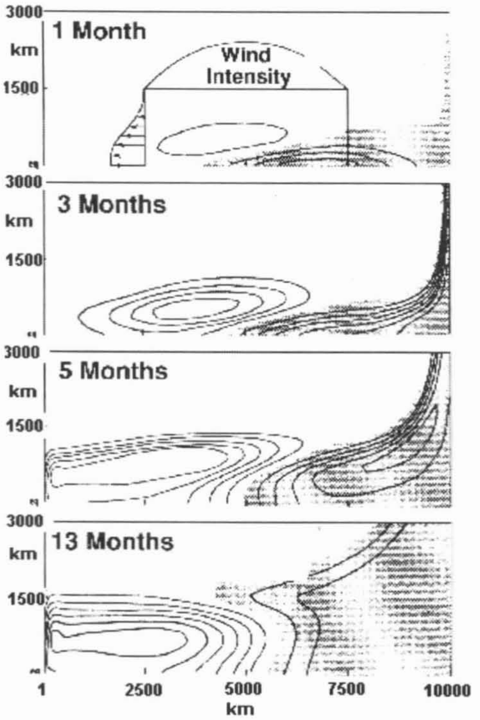

Figure 8. The development of sea level with time by an easterly wind stress (maximum of 0.5 dyne/cm^2) distributed as indicated in the box in the 1st month. Sea-level contour is 10 cm, the zero contour is omitted, and the shaded area is negative (after McCreary 1985).

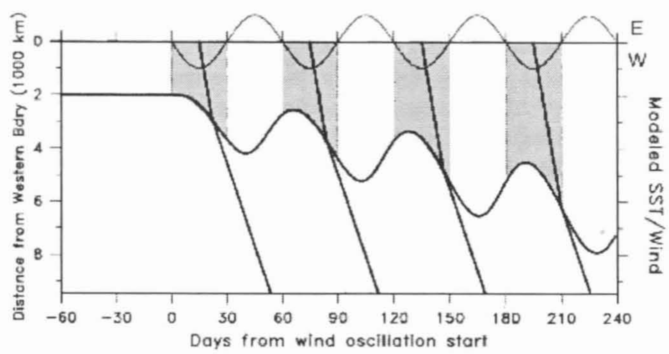

Figure 9. A model version of 4 successive Kelvin waves driven by the sinusoidal winds at the top of the graph. Although the plot shows the oscillation of the leading edge of the warm pool, it could equally well describe the deepening of the 20°C isotherm (after Kessler et al. 1995a).

'Rossby radius', here about 3° of latitude. Poleward-moving waves trapped against an eastern shoreline are also Kelvin waves.

Figure 8 shows the model development of equatorial North Pacific sea level with an easterly wind-stress box in the Central Pacific. In month 1, surface water moves NW, building a warm hill off the western equator and leaving a cool depression on the eastern equator. By month 13 there is a well developed western Warm Pool with a 90 cm difference in sea level across the Pacific and a corresponding 100 m difference in thickness of the thermocline. In the absence of other influences, this might be a stable configuration, with the westward moving surface water balanced by the eastward Equatorial Undercurrent.

ENSO's Kelvin waves are generated by a reversal of the wind in Figure 8, but differ in that the eastward-moving elevation is on the equator. Such waves in the eastern Pacific can displace the depth of the 20°C isotherm by 8 m/day over a vertical range of 100 m (Kessler et al. 1995a).

Figure 9 shows that it is not necessary to have steady westerlies to produce eastward motion of the Warm Pool. 2 to 4 downwelling Kelvin waves 60 days apart per year, driven by the Madden-Julian Oscillation (MJO) described below, will closely reproduce the observed thermocline deepening. This model lacks heat exchange, assumes an infinite Warm Pool, and its winds are artificially regular and strategically located, but it makes the point that the greater inertia of the ocean provides a phase lag which allows partial rectification of sinusoidal winds to move warm water eastward along the Pacific equator.

At this point it is fair to describe an El Niño as an extension of the process of Figure 9. In a greatly oversimplified picture, if the Warm Pool reaches to the dateline, the effect of such wind forcing will be to drive it the rest of the way across the Pacific.

External Forcing of ENSO

Temporal events

The regularity implied by the model of Figure 9 is not seen in the real system, because there are additional sources of forcing, and each of them is governed by events which are not themselves regular. Among the more important quasi-regular influences are the following:

The highest-frequency influence on ENSO appears to be Tropical Instability Waves, first seen in satellite SST records as a frontal system north of the equator oscillating with a 20 to 30 day period (Legeckis 1977). They are apparently generated by current shear in the complicated equatorial-current system, and induce large meridional velocities which advect heat 'sideways' to the more noticeable zonal flows. They are typically absent in the boreal spring.

Next comes the Madden-Julian Oscillation (MJO) (Madden and Julian 1971, 1972), which is an atmospheric convection center arising in the central Indian Ocean equator. A radially symmetric convection center will experience a net eastward force because inflowing surface west winds converge toward the center and east winds diverge, just as in Figure 6. As the MJO intensifies, it moves east at 3 to 6 m/s (250 to 500 km/day). Eventually it leaves the Indian Ocean, transits the Indonesian Archipelago without disintegrating, and finally merges with the convection center at the eastern edge of the Warm Pool. As its own eastern fetch shortens and its easterly winds decrease, it generates eastward-propagating Kelvin waves which progress at least as far as the Banda Sea (Sprintall et al. 2000b) and may reach the Warm Pool, like those in Figure 9. Meanwhile, a replacement convection cell is growing in the center of the Indian Ocean. The observed period of this process is 30 to 100 days (Kessler and McPhaden 1995b). The MJO is a fairly regular contributor of input to ENSO, but is uncorrelated with its output (Kessler 2000).

Annual oscillations such as the north-south movement of the ITCZ, and the Indian monsoon, are important, although

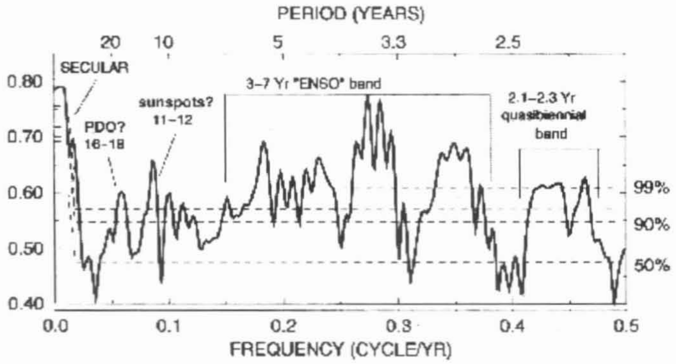

Figure 10. The power spectrum of ENSO. The energy in the 3 to 7-year band is apparently El Niño's own.. The pattern is not incompatible with a chaotic mode in a basically rhythmic system (After Allan 2000).

their relative influence may change by more than a factor of 2 over the course of a decade. Donohue and Wimbush (1998) note annual frequencies in models (McCreary and Yu 1992) and observations (Luther and Johnson 1990), and find 2 latitudes in their model where shear can convert seasonally varying mean-flow energy into eddies. It may be that shear instabilities can arise between any pair of the numerous (and seasonally irregular) equatorial currents.

The 55-Sv North Equatorial Current bifurcates at the Philippines, feeding the 30-Sv north-flowing Kuroshio and the 25-Sv southwest-flowing Mindanao Current. The bifurcation point changes seasonally in response to wind stress, creating a quasi-annual 40 cm swing in sea-level offshore of Indonesia (Qui and Lukas 1996). (Sv = Sverdrup = 10^6 m^3/sec)

The Tropical Biennial Oscillation (TBO) is an alteration of the convective strength of the Indian monsoon (Slingo 1999) which may be responsible for the minor 2-year peak observed in the ENSO power spectrum of Figure 10. There is another Quasi Biennial Oscillation (QBO) defined in terms of the direction of equatorial stratospheric winds whose relation to TBO I have not seen discussed.

The 'ENSO band', covering three to seven years in the power spectrum, is apparently not attributable to external forcing, but contains frequencies intrinsic to ENSO.

Inevitably, the 11-year solar sunspot cycle shows up as a minor peak.

A much slower disturbance is the Pacific Decadal Oscillation (Francis and Hare 1994; Hare and Francis 1995). Defined as the leading principal component of North Pacific monthly SST variability (poleward of 20°N), it affects sea level, wind stress and salmon over the entire Pacific. Its cause is unknown, and the record is too short to decide whether this is a true oscillation. (Between 1900 and 1935 the PDO looks like noise. Its later excursions might be correlated with a ripple in the global mean temperature discussed in Part II.) In any event, its height changes have been detected by satellite altimetry.

The period of the PDO—if it has one—is unknown. The data do not exclude the 19-year solar-lunar cycle known since Meton in 432 BC, which shows up in tidal records. This may be responsible for the small 16 to 18-year peak in Figure 10.

Much like the SO, the PDO has one pole centered on Rapa Nui. The other extremum is a horseshoe running from the western North Pacific along the western Pacific to Antarctica.

PDO graphics are on the web, at http://tao.atmos.washington.edu/pdo/. From our point of view, the PDO might be responsible for an 0.5°C decadal variation in SST at Rapa Nui. We will return to the significance of such a variation in Part II.

Penland has examined ENSO with linear inverse models—a mathematically reliable way of analyzing and extrapolating historical data. She finds at least three damped normal modes with periods longer than three years and decay times of 4 to 8 months (Penland and Sardeshmukh 1999), with importance attached to the south Indian and central Pacific oceans (Penland and Matrosova 1994). This is one more long-period mode than itemized above. I have not found it described in the literature, so there appears to be at least one major cyclical influence on ENSO which has not yet been identified. Mechanisms which involve the south Indian Ocean are also scarce in the literature.

External flows

There may be minor meridional flows which affect ENSO, among them, Tropical Instability Waves and subsurface inflow from extratropical convergence zones. These are regarded as second-order effects and, while recognized, have been little studied.

One flow known to be important is the Indonesian Throughflow (ITF). The mean flow is westward, percolating through the convoluted passages of Indonesian Archipelago to the Indian Ocean (Figure 4). Godfrey (1996) computes the ITF from an 'Island Rule' model—which integrates wind stress upwind of the island (*pace* Australia-is-a-continent boosters)—and finds serious departures attributable to tidal and topographic mixing in the Indonesian seas. The importance of the ITF is perhaps best shown by the coarse-grid world-ocean model of Hirst and Godfrey (1993), who found that shutting down the ITF doubled heat absorption in the Pacific Cold tongue.

The ITF is not well characterized. Three recent papers re-

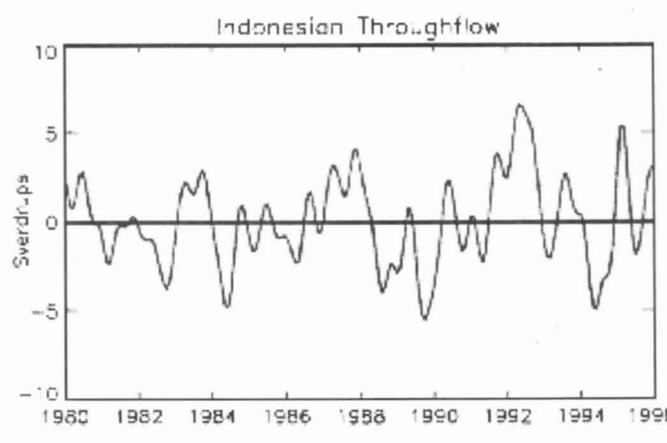

Figure 11. A model estimate of the Indonesian Throughflow, a current which directly affects the Warm Pool. (After Murtugudde and Busalacchi 1998).

port contradictory annual fluxes of -7 ±12 (Wijffels et al. 1996), 15±5 Ganachaud et al. 2000)—who noted that 'because of monsoonal shifts, discussion of the Indian Ocean as a steady-state system is problematic', and 24 Sv (Banks 2000). (Positive values represent westward inflow to the Indian Ocean.) The large difference apparently arises from different estimation methods (ranging from hydrographic sections to computer modelling) and sampling at different times. The consensus value appears to be settling down to –7 ±10 to 15 Sv (John Toole, personal communication), with the uncertainty attributed to internal-wave motions (Fieux et al. 1996). The mean flow is related to the gradient of sea level across the Archipelago, while the variability indicates the possibility of large intermittent wind-driven flows into the Warm Pool.

The computer simulation by Murtgudde et al. (1998) suggests that the net effect of the ITF is to transfer heat from the Pacific to the Indian Ocean, reducing the Warm Pool area by 10% compared to runs in which the Archipelago is sealed shut.

The computed ITF of Figure 11 shows obvious correlations with the SOI of Figure 2 and the ENI of Figure 3. Correlation, it will be recalled, says nothing about causation, and leaves open the question of the extent to which ENSO drives ITF and ITF drives ENSO. In any case, the two form a closely coupled system.

Meyers (1996) finds four distinct currents in the Timor Strait: the eastward South Java Current, the highly variable Westward South Equatorial Current, the eastward Eastern Gyral Current, and the coast-hugging southwestward Leeuwin Current. Unfortunately, no observational data have the time resolution needed to detect flow changes related to the MJO, so the fundamental mechanistic details of how the Indian Ocean influences ENSO remain mysterious.

There's More to Come

I realize that Rapanuiphiles will at this point be disappointed by my coverage of events related to their favorite island. Perhaps they also feel that they have been exposed to rather more physical oceanography than they ever felt a need for. All I can say is that I had to learn all of the above to make sense out of what comes next, before we can begin to think about Rapa Nui.

What comes next (in Part II) will be an examination of selected data, of which there is now a great deal. I guarantee that it is so messy that none of it makes sense until one can see that it is at least distantly related to the simple computer models discussed above.

Finally we will look at how all of this is likely to have affected Rapa Nui in the past. I am hoping to build a sufficient foundation so that we will be able to make rational assessments of the probability of climate change and climate fluctuation on Rapa Nui.

Acknowledgements

I particularly thank Billy Kessler, Vern Kousky, Michael McPhaden, Patrick Nunn, Janet Sprintall, and John Toole, all of whom have patiently held my hand (by e-mail), doing their best to provide reliable data, point me at important papers and ideas, and squelch my flights of fancy.

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